PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
C10M

A2

(11) International Publication Number: WO 99/60079

(43) International Publication Date: 25 November 1999 (25.11.99)

(21) International Application Number: PCT/US99/11350

(22) International Filing Date: 21 May 1999 (21.05.99)

(30) Priority Data:
60/086,247 21 May 1998 (21.05.98) US

(71) Applicant *(for all designated States except US)*: THE TRUSTEES OF COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK [US/US]; Broadway and 116th Street, New York, NY 10027 (US).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: HONG, Shane, Y. [US/US]; Mechanical Engineering Dept., Columbia University, #234 Mudd Building, 500 West 120th Street, New York, NY 10027 (US).

(74) Agents: TANG, Henry et al.; Baker & Botts, LLP, 30 Rockefeller Plaza, New York, NY 10112 (US).

(81) Designated States: JP, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
Without international search report and to be republished upon receipt of that report.

(54) Title: ECONOMICAL CRYOGENIC MILLING TOOL ASSEMBLY WITH ROTARY LIQUID NITROGEN COUPLING

(57) Abstract

Methods and apparatus for delivering a cryogenic cutting fluid such as liquid nitrogen to a cutting tool in a rotatable cutting assembly, including a supply line for supplying cryogenic cutting fluid, a rotatable cutting assembly, and a rotary coupling, are provided. The rotatable cutting assembly includes at least one cryogenic cutting fluid input in a coupling region thereof to receive the cryogenic cutting fluid from the supply line, and at least one cryogenic cutting fluid delivery line. Each cryogenic cutting fluid delivery line is fluidly coupled to at least one input to receive cryogenic cutting fluid from the input, and terminates so as to be fluidly coupled to a cutting portion of said cutting tool to thereby deliver the cryogenic cutting fluid to that cutting portion. The coupling is rotatably attached to the coupling region of the rotatable cutting assembly, and fluidly links the supply line to the cutting assembly inputs so that the cryogenic cutting fluid is permitted to flow from the supply line to the cutting assembly without substantial leakage.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		
EE	Estonia						

Description

Economical Cryogenic Milling Tool Assembly With Rotary Liquid Nitrogen Coupling

Background of the Invention

I. Field of the invention.

The present invention relates to techniques for cooling and lubricating mechanical cutting assemblies, and more particularly, to the use of liquid nitrogen as a coolant in a rotating cutting assembly.

II. Description of the related art.

In a state of the art mechanical cutting assembly, a cutting fluid, typically comprising one or more natural or synthetic oils, is used to improve the performance of the cutting tool by cooling the tool and the workpiece, lubricating the cutting surface of the tool, and flushing waste particles away from the work area. However, the use and disposal of such state of the art cutting fluids raises serious environmental and health related concerns. Some cutting fluids are responsible for such undesirable problems as unpleasant odors, smoke fumes, the formation of harmful bacteria, skin irritations and even cancer. Others generate toxic vapors which can cause illness or even death unless handled with extreme care.

These negative effects are prevalent in metal cutting industries and particularly in those applications where cutting fluids are extensively used. According to one study, reported in Olds, W.J., "Lubricants, Cutting Fluids, and coolants", Ch 19, pp. 177 (1973), more than two million workers in industries using the studied fluids suffered from one or more forms of skin disorders. Moreover, the study found that costs associated with properly treating and disposing used cutting fluid waste was found to be twice its purchasing price in the U.S. and a staggering four times its price in Europe.

In light of these above concerns, the use of cryogenic liquids as a replacement for conventional cutting fluids have been investigated by those skilled with metal cutting processes. Indeed, researchers have reported that cryogenic coolants can increase tool life, improve chip breaking, and refine workpiece surfaces. For example, in Bartle, E. W., "Reducting Machining Times by the Use of Carbon Dioxide Coolant ", *Machinery*, Vol. 83, July, pp. 172-174 (1953), an operating system in which liquid CO_2 supplied through a nozzle (0.009"-0.015" I.D.) at a pressure of 850 psi is described. This study reported a 100% increase in carbide tool life.

In the article by Cerne, P.S., et al., "Central System Distributes CO_2 Coolant for Grinding," *The iron Age*, Aug., pp. 126-128 (1952), a large, central system for supplying liquid CO_2 in a grinding application, with the benefit of realizing a 250% increase in grinder productivity, is reported. In another study, Gruman Aircraft Engineering, "Cryogenic Coolants Speed Titanium Machining", *Machinery*, July, pp. 101-102 (1965), the environmentally safe use of liquid nitrogen in a milling application was reported. In the study, oil coolant, CO_2 and L N_2 were used to compare the machining of titanium. The liquid nitrogen milling showed a tool life 3.5 times longer than the result obtained using oil.

Although the success of cryogenic machining was reported in 1950s and 1960s, the technology was abandoned in 1970s both due to the high costs associated with early cryogenic technology, and since some materials become harder under cryogenic temperatures, making them more difficult to be machined.

However, modern research has paved the way for the efficient use of refrigerated liquid gases. For example, in Hong. S.Y., "Advancement of Economical Cryogenic Machining Technology", *Third International Conference on Manufacturing Technology* (1995), a study emphasizing the economic use of liquid nitrogen is presented. Nitrogen is abundant, inert, harmless, and may be naturally recycled. Accordingly, the time is ripe for the art to advance to the efficient utilization of cryogenic liquids in a mechanical cutting assembly,

thereby fully satisfying the long felt need form an environmentally safe and economical cooling technique for such assemblies.

Summary of the Invention

An object of the present invention is to provide a clean and environmentally safe, yet highly productive and economical cooling technique in a mechanical cutting assembly.

Another object of the present invention is to provide a technique for efficiently using liquid nitrogen as a cryogenic coolant in a mechanical cutting assembly.

A further object of the present invention is to lower operating costs and increase production efficiencies in a mechanical cutting assembly.

Yet another object of the present invention is to eliminate burns, chemical changes, and the appearance of rough surfaces on a mechanical cutting assembly workpiece caused by coolant residue build up on edges of the tool and by the cutting itself.

In order to meet these and other objects which will become apparent with reference to further disclosure set forth below, the present invention an apparatus for delivering a cryogenic cutting fluid such as liquid nitrogen to a cutting tool in a rotatable cutting assembly, including a supply line for supplying cryogenic cutting fluid, a rotatable cutting assembly, and a rotary coupling. The rotatable cutting assembly advantageously includes at least one cryogenic cutting fluid input in a coupling region thereof to receive the cryogenic cutting fluid from the supply line, and at least one cryogenic cutting fluid delivery line. Each cryogenic cutting fluid delivery line is fluidly coupled to at least one input to receive cryogenic cutting fluid from the input, and terminates so as to be fluidly coupled to a cutting portion of said cutting tool to thereby deliver the cryogenic cutting fluid to that cutting portion. The coupling is rotatably attached to the coupling region of the rotatable cutting assembly, and fluidly links the supply

line to the cutting assembly inputs so that the cryogenic cutting fluid is permitted to flow from the supply line to the cutting assembly without substantial leakage.

In one preferred arrangement, the supply line includes a vacuum jacket, and the rotatable cutting assembly includes both a tool holder member and a sleeve member circumferentially encompassing the tool holder member. In such an arrangement, each of the cryogenic cutting fluid inputs are holes in the sleeve member, and each cryogenic cutting fluid delivery line is fluidly coupled to a corresponding hole in the sleeve member. The cryogenic cutting fluid delivery lines may be formed by a channel bored into the tool holder member or a tube mounted on the tool holder member, and most preferably are 1/16 of an inch diameter vacuum jacketed tubes.

The tubes may be cut at an angle β relative to the flow of the cryogenic cutting fluid to induce a spreading of the cryogenic cutting fluid to effect distribution upon a wearing area of the cutting portion of the cutting tool. Alternatively, in a preferred arrangement, at least one nozzle is mounted on the tool holder member and coupled to a tube to receive the cryogenic cutting fluid from the tube and distribute the cryogenic cutting fluid upon the wearing area of the cutting portion of the cutting tool.

In an especially preferred arrangement, the rotary coupling includes a casing and a ring-shaped seal member. The casing has an outside surface thereof, a circular cutting assembly opening forming an inside surface thereof, and at least one cryogenic cutting fluid channel traversing the casing from a portion of the outside surface to a portion of the inside surface. In this arrangement, each cryogenic cutting fluid channel is fluidly coupled to a supply line at the outside surface to permit the cryogenic cutting fluid to flow from the supply line to the inside surface

The ring-shaped seal member is advantageously constructed with a first surface being sealably coupled to a portion of the coupling region of the rotatable cutting assembly, a second surface coupled to a portion of the inside surface of the casing, and an opening traversing the seal member from the inside surface to

the outside surface and aligning with both a cryogenic cutting fluid channel and an inputs to permit the cryogenic cutting fluid to flow from the inside surface of the casing to the rotatable cutting assembly. The seal member should be constructed from material capable of elastic deformation at both room temperature and a temperature of said cryogenic cutting fluid, and most preferably comprises Teflon®. Likewise, it is preferred that the inner surface of the seal member includes at least one lip on opposite sides of the opening so that at least a first lip is sealably coupled to a portion of the coupling region of the rotatable cutting assembly on a first side of the input, and a second lip is sealably coupled to a portion of the coupling region of the rotatable cutting assembly on an opposite side of the input.

In accordance with another preferred aspect of the present invention, the inside surface of the casing includes a groove at a rotatable coupling portion thereof and the coupling region of the rotatable cutting assembly has a corresponding groove at a rotatable coupling portion thereof. In such an arrangement, a plurality of ball bearings are placed in the channel defined by the grooves to effect rotatable coupling of the rotatable cutting assembly and the rotary coupling.

The present invention also provides a method for delivering a cryogenic cutting fluid from a fixed supply line to a cutting edge of a rotatable cutting assembly. The method involves the steps of (a) supplying a cryogenic cutting fluid from a fixed supply line to at least one cryogenic cutting fluid input in a rotatable cutting assembly substantially without leaking therebetween; (b) delivering the cryogenic cutting fluid supplied to the inputs through at least one cryogenic cutting fluid delivery line; and (c) applying substantially all of the delivered cryogenic cutting fluid to the cutting edge of the rotatable cutting assembly.

In a preferred technique, the supplying step involves receiving a cryogenic cutting fluid from the fixed supply line, passing the cryogenic cutting fluid through at least one channel in a housing member of a rotary coupling, and

advancing the cryogenic cutting fluid through at least one channel in an elastically deformable seal member of said rotary coupling to supply the inputs with cryogenic cutting fluid while substantially avoiding leaks. The delivering step may involve delivering the cryogenic cutting fluid through at least one channel bored into said rotatable cutting assembly, or alternatively, through at least one tube mounted on the rotatable cutting assembly.

In one preferred technique, the applying step requires expelling the cryogenic cutting fluid from expelling ends of the cryogenic cutting fluid delivery lines formed an angle β relative to the flow of the cryogenic cutting fluid, to thereby induce a spreading of the cryogenic cutting fluid and to distribute the cryogenic cutting fluid upon a wearing area of the cutting portion of the cutting tool. In a highly preferred alternative method, the applying step requires passing the delivered cryogenic cutting fluid through at least one nozzle to distribute the cryogenic cutting fluid upon a wearing area of the cutting portion of the cutting tool.

The accompanying drawings, which are incorporated and constitute part of this disclosure, illustrate preferred embodiments of the invention and serve to explain the principles of the invention.

Brief Description of the Drawings

Fig. 1 is a system diagram of an embodiment of the present invention.

Fig. 2A is a side view of a standard cutting tool.

Fig. 2B is a bottom view of a standard cutting tool.

Fig. 3 is a cut away side view of a cutting assembly and rotary coupling in accordance with an embodiment of the present invention.

Fig. 4 is a side view of cutting assembly shown in Fig.3.

Fig. 5A is a schematic drawing of a cutting assembly shown in Fig.3.

Fig. 5B is a schematic of sleeved portion of the cutting assembly shown in Fig.3.

Fig. 6A is a schematic top view of a sleeve used in the cutting assembly shown in Fig.5.

Fig. 6B is a schematic side view of a sleeve used in the cutting assembly shown in Fig.5.

Fig. 7A is a schematic top view of a top plate used in the rotary coupling of Fig.3.

Fig. 7B is a schematic side view of a top plate used in the rotary coupling of Fig.3.

Fig. 8A is a schematic top view of a middle plate used in the rotary coupling of Fig.3.

Fig. 8B is a schematic side view of a middle plate used in the rotary coupling of Fig.3.

Fig. 9A is a schematic side view of a coupling housing member used in the rotary coupling of Fig.3.

Fig. 9B is a side view of the coupling housing member used in the rotary coupling of Fig.3.

Fig. 9C is a side view of the coupling housing member used in the rotary coupling of Fig.3.

Fig. 10A is a schematic side view of a Teflon seal used in the rotary coupling of Fig.3.

Fig. 10B is an enlarged schematic side view of the Teflon seal used in the rotary coupling of Fig.3.

Fig. 11A is a schematic top view of a distribution ring used in the rotary coupling of Fig.3.

Fig. 11B is a schematic side view of the distribution ring used in the rotary coupling of Fig.3.

Fig. 11C is an enlarged schematic side view of the distribution ring of Fig.11B.

Fig. 12A is a schematic of a crimped transfer tube in accordance with an embodiment of the present invention.

Fig. 12B is a schematic illustrating spray pattern from the crimped tube of Fig.12A.

Fig. 13A is a schematic top view of a nozzle used in the apparatus shown in Fig.3.

Fig. 13B is a schematic side view of the nozzle shown in Fig.13A.

Fig. 13C is a schematic side view of the nozzle shown in Fig.13A.

Fig. 13D is a schematic section taken along line A-D of Fig.13A.

Fig. 13E is a schematic bottom view of the nozzle shown in Fig.13A.

Fig. 14 is a graph showning comparative test results.

Description of the Preferred Embodiments

Referring to Fig. 1, the principals which underlie the present invention will now be described. Fig. 1 illustrates an apparatus 100 for delivering a cryogenic cutting fluid to a cutting tool in a rotatable cutting assembly. A cutting assembly 110 is capable of rotation about an axis 111, an can move up and down in a direction parallel to the axis 111 in accordance with desired cutting. A conventional cutting tool 120 may be mounted on the cutting assembly 110 in any manner know to those skilled in the art, or alternatively may form an integral part of the cutting assembly 110. The cutting tool 120 terminates at a cutting edge 130 where mechanical cutting of a workpiece is to occur.

In accordance with the present invention, a cryogenic cutting fluid such as liquid nitrogen is supplied from a storage tank (not shown) via a supply line 140. Due to the low temperatures associated with commonly available cryogenic fluids, the supply line 140 should be vacuum jacketed. While the foregoing preferred embodiment is described with liquid nitrogen as the cutting fluid, it should be understood that other cryogenic fluids, such as liquid argon or liquid carbon dioxide, may be readily usable in the system depicted in Fig. 1. Likewise, although only one supply line 140 is shown in Fig. 1., two or more supply lines could be incorporated if desired.

The supply line 140 feeds the cryogenic cutting fluid to a liquid nitrogen distribution system 150, to be described in greater detail below. The liquid nitrogen distribution system 150 incorporates a rotary coupling to rotably attach and fluidly link the cutting assembly 110 to the fixed supply line 140 so that during operation, the cryogenic cutting fluid is permitted to flow from the supply line to the cutting assembly without substantial leakage therebetween.

Also shown in Fig. 1., a transfer tube 160 is mounted on the cutting assembly 110 and cutting tool 120. As described in further detail below, the transfer tube 160 receives the cryogenic cutting fluid from the liquid nitrogen distribution system 150 and delivers the fluid to the cutting edge 130 of the cutting tool 120. Although only one transfer tube is shown in Fig 1., two or more transfer tubes may be desirable depending on the number of flutes, grooves or cutting edges in the cutting tool, and it is preferred that one transfer tube is used for each such flute or groove.

The cutting tool 120 is shown in greater detail in Fig 2. While the tool may have considerable surface area, it is wasteful to treat the entire surface with the cryogenic cutting fluid. As shown in the side view of Fig 2A, the cutting edges B are subjected to flank wear and margin wear which tends to chip away at the cutting point of the tool. As shown best in the bottom view of Fig 2B, the cutting edges A are also subjected top flank wear which tends to thin the cutting edge. It is these two forms of wear that need to be reduced to prolong tool life. Accordingly, it is preferable to spray the cryogenic cutting fluid only on the cutting region 130 of the tool 120.

In operation, liquid nitrogen is transferred from a storage tank to the cutting edges 130 of the cutting tool 120 while the tool rotates. Due to extremely low temperature of the liquid nitrogen, its direct contact with the work piece would make the materials to become harder, making them more difficult to be machined. Thus, transfer tubes 160 should be mounted on the tool so that the liquid nitrogen is only injected to the cutting edges of the tool and not onto the work piece.

The selective injection of a cryogenic coolant also economizes on the consumption rate of the liquid nitrogen, which can be rather expensive. A rough calculation of the consumption rate is based on the cutting energy for each material and the specific cutting conditions. As further described in Guyer, E.C., *Handbook of Applied Thermal Design*, McGraw-Hill, 1989, 11, 2-18, the disclosure of which is incorporated by reference herein, the flow rate, Q, can be obtained from Eq. (1):

$$Q=\frac{k_c F_c v_c}{2750 K_{eff} \gamma \rho} \qquad (1)$$

where: Q is the coolant flow rate (Gal/min), k_c is the coefficient of cooling rate, F_c: is the cutting force (lb), v_c is the cutting speed (fV min), K_{eff} is a constant equal to 0.85· γ is the heat of vaporization of LN_2 as supplied, or 112 (kJ/kg), and ρ is the density of the LN_2 at the saturate state at 295 psi, or 0.571 (kg/m^3).

Under different cutting speeds, the cutting force can be obtained from Eq. (2):

$$Pm=\frac{F_c v_c}{33,00} \qquad (2)$$

where Pm is the machining power which may be calculated using Eq. 3 and 4:

$$Zw=a_c a_p v_f \qquad (3)$$

$$Pm=p_s Z_w \qquad (4)$$

where p_s is the specific cutting power (hp), Z_w is the metal removal rate (in^3/min), a_e is the cutting width (inch), a_p is the cutting depth (inch), and v_f is the feed rate (inch/min).

Based on above equations, the cutting force, Fc, and the theoretical flow rate of liquid nitrogen may be calculated as listed in Table I.

Table I: Estimated Flow Rate Requirement in Cutting Different Materials

Materials	Depth of cut (inch)	Width of cut (inch	Feed Rate (inch/min)	Cutting Speed (ft/min)	Cutting Force (lb)	Flow rate (gal/min)
AISI 1018	0.03	0.40	4.30	100.0	52.79	0.014-0.07
AISI 4140	0.03	0.40	4.80	120.0	71.28	0.023-0.12
Ti 6 Al 4V	0.03	0.40	4.00	100.0	69.70	0.018-0.09
Aluminum (A390)	0.03	0.40	16.20	400.0	14.43	0.015-0.08
Aluminum 6160	0.03	0.40	8.53	200.0	15.20	0.008-0.04
PVC	0.03	0.40	24.40	500.0	2.22	0.003-0.015

The values of flow rate represents the minimum amount required in the milling process. According to the estimation, a cryogenic milling process can be very economical because the required liquid nitrogen consumption is so small.

Referring next to Fig. 3, one preferred embodiment of the liquid nitrogen distribution system 150 and cutting assembly 110 is shown. A cutting assembly 110 suitable for engagement with a cutting tool 120 (not shown) includes a full diameter portion 310, a ball bearing groove 311, a reduced diameter portion 312, a tool engaging portion 313, and one or more slots 314 leading into a space 315 at the end of the assembly. The assembly 110 may be fabricated from any suitable steel, such as Kiex5R-1.00-LF2.5-4 or other materials that retain strength under disparate temperature conditions ranging from cryogenic temperatures through 500° F.

The reduced diameter portion 312 should be slightly less wide than the full diameter portion 310 to provide for a sleeve 320 circumscribing the upper portion of the reduced diameter portion 312, where coupling to the liquid

nitrogen supply line 140 is to occur. Thus, as shown best in Fig. 4, the full diameter portion 310 and the reduced diameter portion encompassed by the sleeve 320 are of nearly equal diameter and are separated by the groove 311.

The sleeve includes one or more openings 321 to permit the cryogenic fluid to pass into the assembly 110. Returning to Fig. 3, each opening 321 in the sleeve 320 is connected to a transfer tube 380 which may terminate a nozzle 390.

A seal member 360, 361 and a seal casing including top plate 330, middle plate 340, housing member 350, and a distribution ring 370 form rotary coupling 400. The top plate 330, middle plate 340 and housing member 350 include screw holes 331 so that a screw (not shown) may be used to sandwich the coupling 400 together, with the housing member forming the lower and side faces of coupling, and the seal 360, 361 and distribution ring 370, described in greater detail below, sandwiched therein.

The housing member 350, seal 360, 361 and distribution ring 370 include a channel 365 to permit the cryogenic fluid to pass through the coupling 400 at an aperture defined by the termination of the channel 365 to become incident on the sleeve 320 of assembly 110. The a top plate 330, middle plate 340, housing member 350, and distribution ring 370 may be fabricated from any suitable metal or metallic alloy. Due to the use of cryogenic fluids, the material should exhibit low thermal conductivity and be resistant to oxidation, such as stainless steel.

Since the top plate 330, middle plate 340, and housing member 350 are fabricated out of metals and encompass the assembly 110, it is required that they are cut with openings that are slightly larger than the diameter of the assembly to permit for thermal contraction while avoiding contact of the assembly 110. Thus, where the assembly is turned to a one inch diameter inclusive of sleeve 320, the openings should be approximately 1.01 or 1.02 inches.

The top plate 330 and middle plate 340 are also fabricated so as to form a groove 341 at the inner portion thereof. The groove 311 in assembly 110 and the groove 341 formed at the interface of top plate 330 and middle plate 340 are

preferably form 90 degree angles, with each grove face aligned at a 45 degree angle from the surface of the assembly 110.

The grooves 311, 341 create a channel which is filled with one or more ball bearings 335. The ball bearings should be fabricated from the same material as the top plate 330 and middle plate 340. Thus, in the embodiment described with respect to Fig. 3, 1/16 of an inch stainless steel ball bearings are preferred. By using the same materials, the ball bearings and the plates of the rotary coupling 400 have the same thermal expansion coefficient, and hence are functionally insulated from temperature variations. Likewise, the rotary coupling is given a self-centering property due to the v-groove design.

Through the ball bearings 335, the rotary coupling 400 mechanically couples the fixed rotary coupling 400, including cryogenic cutting fluid supply line 140, to the rotatable cutting assembly 110. The rolling contact between the coupling 400 and the assembly 110 reduces rotational friction and torque to permit freer rotation of the assembly 110. Through the use of the specially designed seal member 360, 361, the rotary coupling 400 also permits the cryogenic cutting fluid to flow from the supply line 140 to the cutting assembly 110 through channel 351 and hole 321, while preventing loss of cutting fluid at the juncture between those parts.

A technique for adapting a commercially available assembly, such as a milling tool holder, into an assembly suitable for use in the present invention is described with reference to Figs. 5(a)-(c). As was also shown in Fig. 3, the commercially available assembly includes a full diameter portion 510, a reduced diameter portion 512, and a tool mounting portion 540. For a one inch diameter assembly, the full diameter portion 510 will measure approximately one inch in diameter while the reduced diameter portion 512 will measure approximately 13/16 of an inch in diameter.

Using a commercially available milling cutter, slots 530 are cut into the reduced diameter portion 512 of the assembly approximately 2/10 of an inch deep from the surface of the assembly. The number of slots preferred for the cutting

assembly will depend on the geometry of the cutting tool to be held by the assembly; with one slot for each flute being preferred. As best shown in Fig. 5(c), each slot 530 is approximately 0.125 inches wide and begins approximately 0.19 inches below the interface between the full diameter portion 510 and the reduced diameter portion 512, and continues along the axis of the assembly to the tool attachment area 540. The slots thus act as a channel in the assembly 110 through which the cryogenic cutting fluid may flow, e.g., through transfer tubes 380.

As shown in Fig. 5(a), the reduced diameter portion 512 of the assembly is encompassed by sleeve 520. Referring to Figs. 6(b) and 6(b), the ring-shaped, stainless steel sleeve 520 is approximately 0.91 inches in diameter as measured from its inside surfaces, approximately 1.04 inches in diameter as measured from its outside surfaces, and approximately 0.509 inches wide. 1.6 inch long transfer tubes 380 are attached to the inner surface of sleeve 520 by silver soldering.

The sleeve 520 with attached tubes 380 is mounted to assembly 110 in accordance with the following preferred technique. First, the assembly 110 is cooled to liquid nitrogen temperature and the sleeve 520 is heated in an oven to 200° Celsius. The heated sleeve is then placed over the cooled assembly with tubes 380 fitting into slots 530, and is shrink fitted onto the assembly, thereby ensuring a tight junction. The sleeve is then machined and polished down to 0.998 - 0.999 inches to match the hole - shaft clearance and tolerance between 110.

Next, the v-shaped groove 511 is machined from assembly 110 and polished. As shown in Fig. 5(a), the faces of groove 511 form an approximately 90 degree angle, with the center of the groove being located approximately 0.270 inches from the top of hole 521 and approximately 0.080 inches from the top of sleeve 520. The groove is cut deep enough into full diameter portion 510 of assembly 110 so as to obtain a width of approximately 0.078 - 0.083 inches.

Finally, as shown in Fig. 5(b), leading indentations 522 are made in the sleeve 520 by a hand held power tool into the soldered transfer tubes 380. As

best shown in Fig. 6(b), each hole 521 is approximately 1/16 of an inch in diameter and is drilled at a downward 30 degree angle with respect to the normal to the inside surface of the sleeve. The holes 521 are drilled so that the top edge of the hole is approximately 0.1785 inches from the top of the sleeve.

Referring to Figs. 7 - 11, the design of a preferred rotary coupling 400 will be explained in more detail. As shown in Fig. 7(a) and 7(b), the top plate 330 is ring shaped, measuring approximately 1.850 and 1.01 - 1.02 inches in outer and inner diameters, respectively, and being approximately 0.060 inches thick. As best shown in Fig. 7(b), the inside opening of the ring is cut at an angle of approximately 45 degrees with respect to the plane of the ring and starting at a diameter of approximately 1.073 - 1.078 inches, so as to form one face 701 of the v-shaped groove 341 in rotary coupling 400. Four equally spaced 1/8 of an inch screw holes 331 are drilled through the plate, each centered 0.825 inches from the center of plate. Finally, 0.01 x 0.02 inch corners 710 of the plate are broken off.

Referring to Figs. 8(a) and 8(b), the middle plate 340 is also ring shaped, measuring approximately 1.850 and 1.01 - 1.02 inches in outer and inner diameters, respectively, being approximately 0.100 inches thick. The face of the inside opening of the ring which is to contact the top plate is cut at an angle of approximately 45 degrees with respect to the plane of the ring and starting at a diameter of approximately 1.073 - 1.078 inches, so as to form the second face 801 of the v-shaped groove 341 in rotary coupling 400. A larger disc 820 is milled from the opposite face of the middle plate which is to contact the seal 360 with a diameter of approximately 1.250 inches and depth of up to 1/64 of an inch. Finally, as with the top plate, four equally spaced 1/8 of an inch screw holes 331 are drilled through the plate, each centered 0.825 inches from the center of plate, and 0.01 x 0.02 inch corners 810 of the plate are broken off.

Referring to Figs. 9(a) - (c), the housing member 350 takes the form of a U-shaped ring, measuring approximately 1.850 and 1.01 - 1.02 inches in outer and innermost diameters, respectively, and being approximately 0.456 inches

thick. As best shown in Fig. 9(b), the ring shaped portion 900 of the housing is approximately 0.10 inches thick and includes an opening 902 having a diameter of approximately 1.390 inches. One face 901 of the ring shaped portion 900 is to contact the middle plate 340, and 0.01 x 0.02 inch corners 903 of the portion are broken off.

Also as shown in Fig. 9(b), the U shaped portion 910 of the housing member 350 is approximately 0.356 inches wide and 1.490 inches in outer diameter, and includes the inner most opening 912. A larger disc 911 that is to contact the seal 361 is milled from the inside of the housing member, having a diameter of approximately 1.250 inches and depth of 0.406 inches from the top surface 901. The still larger opening 902 that is to house the distribution ring 370 is milled from the inside of the housing member to a depth of 0.306 inches from the top surface 901. Four equally spaced 1/8 of an inch screw holes 331 are drilled through the plate, each centered 0.825 inches from the center of plate, and 0.07 x 0.07 inch corners 913 of the plate are broken off. Finally, a 3/32 of an inch wide slot 920 is milled into the housing member to obtain a depth of 0.225 inches from the top surface 901. The slot 920 serves as the channel 351 through the housing member 250 for the cryogenic coolant delivered via line 140.

Referring to Figs. 10(a) - (c), the preferred seal member 360 is also ring shaped, measuring approximately 1.250 in outside diameter and being approximately 0.1734 inches thick, and measuring approximately 0.10100 inches in an innermost diameter defined by the inside surfaces 1011, 1012 of lips 1010, 1020. The face 1001 of the portion of the seal which is to contact the middle plate is cut at an angle of approximately 64 degrees with respect to the plane defined by the face and starting at a diameter of approximately 1.076 inches, so as to form the top surface 1012 of a first lip 1010 in the seal.

A channel approximately 0.020 inches wide is formed from the Teflon® seal to form the bottom surface 1013 of lip 1010 and the top surface 1022 of lip 1020. This channel is also cut at an angle of approximately 64 degrees with

respect to the plane defined by the face 1001, and is cut such that the top surface 1022 of lip 1020 begins 0.017 inches above the bottom face 1002 of the seal, the bottom surface 1013 of lip 1010 begins 0.070 inches above the bottom face 1002, and the two surfaces 1013, 1022 terminating approximately 0.120 inches above the bottom face 1002, as shown in Fig. 10(b).

A second channel, also approximately 0.020 inches wide, is formed from the Teflon® seal to form the bottom surface 1023 of lip 1020. The second channel is also cut at an angle of approximately 64 degrees with respect to the plane defined by the face 1001, cutting into the bottom surface 1002 from approximately 0.105 inches from the outside surface 1003 of the seal to approximately 0.025 inches from the inside surface 1021, and terminating approximately 0.050 inches above the bottom face 1002. Finally, 0.02 x 0.02 inch pieces are broken from corners 1004.

The seal member 361 is constructed in an identical manner, except that the lips 1010, 1020 are directed upwards instead of down. Since they are made of Teflon®, the circular cantilever lips 1010, 1020 of the seal members 360, 361 are designed to maintain flexibility even at cryogenic temperatures, and provide extra tolerance to compensate for a thermal dimensional change caused by the change in temperature from room to cryogenic temperatures. Since Teflon® is inherently self-lubricating and the lips 1010, 1020 are the only portion of the seal 360, 361 which contacts the cutting assembly 110, minimal friction and torque is generated through contact with the rotating assembly.

Moreover, since the lips are angularly pointed toward the cutting assembly, they are designed to advantageously utilize pressure caused by the flowing cryogenic coolant to assist with their sealing function. Although one lip, rather than two lips at each side of the cryogenic input would generally be sufficient, the use of a second lip provides for additional leak-proof assurance. Of course, those skilled in art will appreciate that one, two or even three or more lips of different dimensions and positioned at various angles than that disclosed herein as the preferred embodiment could be used as an effective seal without

departing from the scope of the present invention. Likewise, while the preferred seal member is fabricated from Teflon®, other materials, and especially materials constructed form the tetra-floro-ethyne family of polymers, which maintain elasticity at cryogenic temperatures may be suitable for use to construct the seal members 360, 361.

Referring to Figs. 11(a) - (c), the distribution ring 370 is also ring shaped, measuring approximately 1.350 and 1.01 - 1.02 inches in outer and inner diameters, respectively, being approximately 0.220 inches thick. As best shown in Fig. 11(c), the inner face 1110 of the ring includes a v-shaped groove which forms a 90 degree angle centered approximately 0.110 inches from the top and bottom surfaces 1120, 1130 of the ring, and cut into the ring starting approximately 0.050 inches above and below the top and bottom surfaces 1120, 1130, of the ring.

As best shown in Fig. 11(c), the top and bottom surfaces 1120, 1130, of the ring are irregularly shaped, and each include a knife edge with ribs 1121, 1122, and 1131, 1132, respectively, positioned 0.030 and 0.080 inches from the inside ends 1121, 1131 of those ring surfaces, and rising approximately 0.01 inches above the non-peaked surfaces 1124, 1134 to assist in perfecting the seal. The non-peaked surfaces 1124, 1125 are each approximately 0.060 inches from the radial center of the ring, extending so as to form a circular groove in the top and bottom faces of the ring having an approximately 1.250 inch circumference, and thereby leaving approximately 0.1 inch wide mounts 1135, 1126 at the outside surface of the ring. As with other members of the rotary coupling, 0.01 x 0.01 inch corners 810 of the plate are broken off. Finally, a 3/32 of an inch hole 1150 is drilled through the ring from the outside surface to the inside surface so that cryogenic fluid may flow therein.

For effective and economical cooling, the liquid nitrogen must be injected to the cutting edge where tremendous heat is generated. However, since the cutting tool rotates at a high speed, the centrifugal force of the rotating tool tends to repel the coolant if it is sprayed externally. The ideal approach would have the

coolant continuously flow radially outward from the rotating tool to the cutting edge. In accordance with a preferred aspect of the present invention, special tooling to distribute the liquid nitrogen through the rotary cryogenic delivery device to the cutting edge of the cutting tool is provided.

In the embodiment of the present invention shown in Fig 1., the transfer tubes 160 terminate in a region of the cutting tool which lies in close proximity to the cutting edge of the tool. As shown in Fig. 2(a), a typical cutting tool 120 has two areas A and B for each flute which require lubrication and cooling are approximately rectangular in size. Accordingly, for such a tool 120, the transfer tubes 160 should terminate in a manner which directs the cryogenic cutting fluid to these areas A and B.

Referring to Figs. 12(a) - (b), a preferred design for directing cryogenic coolant to areas A and B of a cutting tool 120 is illustrated. The end 131 of a transfer tube 160 is crimped in a plane orthogonal to the normal to the surface of the cutting tube, to create a narrow opening. As best shown in Fig. 12(a), the side of the crimped portion 161 closest to the cutting tool 120 is then filed to create a downward opening 162 is at an angle β with respect to the plane of the tube 160. The angle β of the crimped opening chosen to best spray the cryogenic coolant over the area a, b as shown in Fig. 12(a), and will depend on the particular tool 120 used. Likewise, the left side, with respect to the direction of flow of the cryogenic coolant, of the crimped portion 161 is filed in a similar manner to form a side opening 163 of the crimped portion 161 suitable to spray the cryogenic coolant over area c, d. The areas a, b and c, d correspond to the cutting edges A and B shown in Fig. 2A.

In an alternative embodiment of the present invention shown for example in Fig 3., the transfer tubes 160 do not terminate at the cutting edge of the cutting tool, but instead feed into one or more specially designed nozzles 390 which are designed to spray the cryogenic coolant in an economical pattern covering the cutting edge area. The nozzles 390 are of the low profile chip

breaker type and accordingly reduce potential chip jamming and enable cooling of the cutting tool edges both when the assembly 110 is rotating and stationary.

As shown in Figs. 13(a) - (e), the nozzles 390 are formed from a single rectangularly shaped block if stainless steel, approximately 0.392 inches wide by 0.420 inches long by 0.080 inches deep. As shown best in the top view of Fig. 13(a), one corner 1301 is cut from the nozzle at a 45 degree angle with respect to the straight side 1300, beginning approximately 0.130 inches from the side. A rounded corner 1302 is likewise cut off the nozzle, 0.150 radial inches from a point which lies 0.242 inches from the straight side 1300. The rounded corner 1302 and adjacent sides 1302, 1304 are cut at an angle from the top surface 1307 to bottom surface 1306, such that the bottom surface 1306 is 0.040 inches longer than the top surface 1307 along the rounded corner 1302 and adjacent sides 1302, 1304.

A screw hole 1310 is drilled through the nozzle, centered 0.154 inches from the flat surface 1308 and 0.242 inches from flat surface 1300. Recess 1311 is also preferably milled from top surface 1307 so that a bolt (not shown) used to attach the nozzle to the assembly 110 can be hidden. The size of hold 1310 and recess 1311 should be chosen to nest match the bolt used.

A 1/6 of an inch in diameter hole 1320 is drilled into flat side 1308, approximately 0.33 inches deep, so as to terminate 1321 inside of the nozzle near the corner portion 1301. The channel is to be welded to the end 161 of transfer tube 160 so as to permit a cryogenic coolant to flow into the nozzle from the tube.

As best shown in Fig. 13(e), a 1/16 of an inch wide and 0.04 inches deep recess 1330 is milled from the bottom surface 1306 along a line that is approximately 0.315 inches from flat surface 1308, starting approximately 0.130 inches from flat surface 1300 and continuing for approximately 0.170 inches. Thus, end 1331 of channel 1320 will intersect with an end 1331 of the recess 1330 to permit a cryogenic coolant to flow therebetween.

Finally, a spraying recess 1340 is milled from the bottom surface 1306 of the nozzle along the curved surface 1302. The spraying recess should be milled to be approximately 0.01 inches deep, extending along the entirety of curved surface 1302, and terminating at surface 1304 so as to form a 30 degree angle with respect to the surface 1304. Since the nozzle 390 is attached to the assembly 110 on its bottom side 1306, the recess 1300 and spraying recess 1340 are bounded by the assembly 110.

In operation, cryogenic cutting fluid flows from transfer tube 160 into channel 1320, then between the nozzle 390 and the assembly 110 through recess 1330 and spraying recess 1340, to be sprayed upon the cutting edges 130 of a cutting tool 120. Of course, the particular dimensions described herein are not functioned requirements, and may be modified as necessary to adapt to the dimensions of the assembly 110, cutting tool 120, and transfer tubes 160.

Examples

In order to demonstrate the advantages of the present invention over conventional cooling, an embodiment using ¾ ", 4 flute cutting tools made of M7 high speed steel material was tested. Tool life tests were carried out under three cooling conditions: dry cutting, the conventional emulsion cooling method, and the cryogenic cooling method. The Positool S-1 vertical milling machine with Anilam's Crusader Series M CNC controller was used. The conventional up milling method was used during evaluation. The cutting conditions followed the recommendation from Metcut Research Associates,"Machining Data Hand Book", Machinability Data Center, Cincinnati, Ohio (1980), the disclosure of which is incorporated by reference herein.

For the cryogenic tests, the tip of the nozzle was located about 0.78" away from the cutting tool. A liquid nitrogen flow rate of 0.2 gallons per minute was used in all tests. At this flow rate, the cost of the cryogenic coolant is about

the same as that of conventional emulsion coolant if the coolant disposal cost is included.

The behavior of high speed milling tools was analyzed while cutting six different kinds of most commonly machined materials: AISI 1013 steel, AISI 4140 alloy sheet, titanium 6Al-4V, aluminum 6061, cast aluminum A390, and polyvinyl chloride (PVC).

AISI 1018 steel is a free machining steel of medium strength and ductility. Its modules of elasticity decreases as temperature increases. Average wear of 0.012 inches on the flank surfaces is used to judge tool life. Tool life for dry cutting, conventional cooling, and cryogenic cooling are 0.75, 2.0, and 7.5 cubic inches of moved workpiece materials respectively. This indicates that cryogenic milling performs 10 times better than dry cutting and 2.67 times better than the conventional emulsion cooling. It was clear that cryogenic machining reduced both the flank wear and margin wear.

AISI 4140 is an alloy steel which is used widely where surface hardness is required. It can be heat treated up to 1.5 inches in diameter and it is most suitable for gear and shaft fabrication in the machinery industry. The cryogenic cooling system performed much better and its effectiveness in increase tool life was obvious. Tool life was increased 390% over dry cutting. The trend of tool wear showed that the tool can last longer with the cryogenic method.

Titanium is a relatively light weight metal with excellent corrosion resistance and high strength-to-weight ratio. Titanium alloy T1-6Al-4V is the most commonly used type of titanium in the aerospace industry. It is considered a difficult-to-machine material for rapid tool wear and short tool life. Tool wear was fast in dry cutting. As the tool becomes blunt the cutting forces rise quickly. This call a rise in temperature at the cutting zone. The heat accumulates on the thin cutting edge of the tool and causes quick tool failure. Due to the low temperature of liquid nitrogen, the temperature of the tool was maintained at a much lower temperature for a longer period of time and yielded the lowest tool wear. Cryogenic cooling increased the tool life by 320% over dry cutting.

Aluminum 6061 is the most used wrought aluminum in the industry. At a high cutting speed of 200 ft/min, the cryogenic cooling method generated rapid tool wear during the first stage of the milling. The rapid wear was caused by a cooled workpiece as the strength of Al 6160 increases with a decrease in temperature. The tool wear rate decreased as the milling progressed and the cryogenic cooling performed very well overall. Because aluminum 6061 is a relatively easy to machine material, the tool lasted too long to complete the tool life testing. The result, however, shows die general trend of cooling performance.

The hypereutectic Al-Si cut alloy, A390, has superior wear characteristics over any other aluminum cast alloys. This material is difficult to machine because of its abrasive property. Although mot wear is relatively slow, the difference in tool wear with or without cooling is clear. The cryogenic cooling method was much better than the conventional cooling method. Tool wear using the cryogenic cooling method was only 10% of that using conventional cooling methods.

Polyvinyl Chloride (PVC) is the only non-metallic material tested. PVC compounds are usually ductile and tough. This material is included in the test because it is not compatible with conventional coolant. The test results shows the tool wear in cutting this material is insignificant in all cooling conditions. Dry cutting generally performs well and should be the preferred machining method. In the cutting test using the cryogenic cooling method, tool wear is less than other methods of cutting. For 0.006 inches of tool wear criteria used, tool life has been increased about 130% over both dry cutting and conventional cooling.

The tool life increase using the cryogenic cooling method is listed in Table 2. Notice that the tool life criteria are different for different materials. For relatively soft materials such as PVC, the tool wear was extremely slow and the experiment could not be continued until tool wear reached the tool life measurement criteria: 0.0236 inches (maximum wear) or 0.0118 inches (average

wear). Therefore different criteria were used to compare different cooling methods and they are listed in Tables 2 and 3.

TABLE 2: TOOL LIFE INCREASE UNDER HIGH CUTTING SPEED

	Cutting speed ft/min	Tool life Criteria Flank wear	Tool life ratio over dry cutting	
			Cryogenic	Coolant
AISI 1018	100	0.015 in	350%	300%
AISI 4140	120	0.011 in	390%	180%
Ti 6-4	100	0.01 in	320%	120%
Al 6160	200	0.0015 in	270%	30%
A390	400	0.0035 in	>>1000%	170%
PVC	500	0.006 in	130%	0%

In order to get a rough estimation of standard tool life, tool wear trend was computed using a high order polynomial fit through the data points obtained, as shown in Fig. 14. Fig. 14 illustrated tool wear comparison of Aluminum A390 at 2035 RPM cutting speed, 0.03 inch cutting depth, 0.67 inch cutting width and a 16.2 inch/min feed rate. The amount of material removed at the criterion points was calculated from the equation of the curve. This resulted in tool life approximation by the same standards for all materials. In order to consider both the flank and the margin wear, the product of the two types of wear measurements are used in the life of tool evaluation. These values are listed in table 3.

TABLE 3: COMPUTED TOOL LIFE INCREASE OVER DRY CUTTING USING THE PRODUCT OF MARGIN AND FLANK WEAR			
		High cutting speed*	
Material	Tool life Criteria *inches of wear*	Conventional Coolant	Cryogenic Cooling
AISI 1018	0.00236	457%	650%
	0.00118	1174%	3307%
AISI 4140	0.00236	176%	286%
	0.00118	907%	1232%
Ti6A1-4V	0.00236	270%	474%
	0.00118	891%	1543%
Al 6061	0.00236	-41%	>>500%
	0.00118	-24%	>>500%
A390	0.00236	51%	798%
	0.00118	18%	1482%
PVC	0.00236	-6%	31%
	0.00118	-1%	23%

In cutting soft or ductile materials like aluminum alloys and PVC, tool wear is slow and therefore it is not a major concern. However, cryogenic cooling is helpful in reducing the built-up at the edge of the tool which yields in a better surface finish of the work piece. Cryogenic cooling showed better surface quality than all other cooling methods tested and extended tool life more than conventional coolants for all materials tested. The advantage of cryogenic milling is significant especially at high speed cutting.

The environmental and health concerns created through the use of conventional cutting fluids have prompted the need for a safer metal cutting process. With liquid nitrogen, which is naturally recycled, cryogenic milling is a clean and economical operation. Through the economical use of liquid nitrogen,

the present invention provides for a safe and economical alternative to the prior art which is superior to existing techniques, both in terms of safety and greater efficiencies realized in within the cutting process. The use of liquid nitrogen provides for the effective elimination of build-up on tool edges and the significant increase of tool life, while simultaneously permitting high speed machining.

The foregoing merely illustrates the principles of the invention. Various modifications and alterations to the described embodiments will be apparent to those skilled in the art in view of the inventors teachings herein. For example, while the foregoing has been described with liquid nitrogen as a coolant, other cryogenic fluids would be equally suitable and may become advantageous due to economic reasons. Likewise, those skilled in the art will realize that superior channeling of the cryogenic coolant from storage to the rotary coupling and within the assembly would realize greater savings. It will thus be appreciated that those skilled in the art will be able to devise numerous systems and methods which, although not explicitly shown or described herein, embody the principles of the invention and are thus within the spirit and scope of the invention.

Claims

1. An apparatus for delivering a cryogenic cutting fluid to a cutting tool in a rotatable cutting assembly, comprising:
   (a) a supply line for said cryogenic cutting fluid;
   (b) a rotatable cutting assembly, having at least one cryogenic cutting fluid input in a coupling region thereof to receive said cryogenic cutting fluid from said supply line, and including at least one cryogenic cutting fluid delivery line, wherein each of said cryogenic cutting fluid delivery lines are fluidly coupled at a first end to at least one of said one or more inputs to thereby receive said cryogenic cutting fluid from said inputs, and wherein each of said cryogenic cutting fluid delivery lines terminates at a second end so as to be fluidly coupled to a cutting portion of said cutting tool to thereby deliver said cryogenic cutting fluid to said cutting portion; and
   (c) a rotary coupling, rotably attached to said coupling region of said rotatable cutting assembly, and fluidly linking said supply line to said one or more inputs in said cutting assembly such that said cryogenic cutting fluid is permitted to flow from said supply line to said cutting assembly without substantial leakage therebetween.

2. The apparatus of claim 1, wherein said supply line further comprises a vacuum jacket.

3. The apparatus of claim 1, wherein said rotatable cutting assembly comprises a tool holder member and a sleeve member circumferentially encompassing said tool holder member, each of said at least one cryogenic cutting fluid inputs being holes in said sleeve member, and each of said at least one cryogenic cutting fluid delivery lines being fluidly coupled to a corresponding hole in said sleeve member.

4. The apparatus of claim 3, wherein each of said at least one cryogenic cutting fluid delivery lines comprises a channel bored into said tool holder member.

5. The apparatus of claim 3, wherein each of said at least one cryogenic cutting fluid delivery lines comprises a tube mounted on said tool holder member.

6. The apparatus of claim 5, wherein each of said at least one tubes comprise an 1/16 inch diameter vacuum jacketed tube.

7. The apparatus of claim 5, wherein each second end of each of said at least one tubes is cut at an angle β relative to the flow of said cryogenic cutting fluid to induce a spreading of said cryogenic cutting fluid to thereby be distributed upon a wearing area of said cutting portion of said cutting tool.

8. The apparatus of claim 5, further comprising at least one nozzle, mounted on said tool holder member and coupled to a second end of one of said at least one tubes, to receive said cryogenic cutting fluid from said tube and distribute said cryogenic cutting fluid upon a wearing area of said cutting portion of said cutting tool.

9. The apparatus of claim 1, wherein said rotary coupling comprises:

(a) a housing member having an outside surface thereof, a circular cutting assembly opening forming an inside surface thereof and being sufficiently large to encompass said coupling region of said rotatable cutting assembly, and at least one cryogenic cutting fluid channel traversing said housing member from a portion of said outside surface to a portion of said inside surface, wherein each of

said at least one cryogenic cutting fluid channels is fluidly coupled to one of said one or more supply lines at said outside surface to thereby permit said cryogenic cutting fluid to flow from said supply line to said inside surface; and

(b) a ring-shaped seal member having a first surface sealably coupled to a portion of said coupling region of said rotatable cutting assembly, a second surface coupled to a portion of said inside surface of said housing member, and an opening traversing said seal member from said inside surface to said outside surface and aligning with one of said cryogenic cutting fluid channels and with one of said inputs to thereby permit said cryogenic cutting fluid to flow from said inside surface of said housing member to said rotatable cutting assembly.

10. The apparatus of claim 9, wherein said seal member comprises a material capable of elastic deformation at both room temperature and a temperature of said cryogenic cutting fluid.

11. The apparatus of claim 10, wherein said seal member comprises Teflon®.

12. The apparatus of claim 9, wherein said inner surface of said seal member includes at least one lip on opposite sides of said opening, wherein at least a first lip is sealably coupled to a portion of said coupling region of said rotatable cutting assembly on a first side of said input and a second lip is sealably coupled to a portion of said coupling region of said rotatable cutting assembly on an opposite side of said input.

13. The apparatus of claim 12, wherein said seal member comprises a material capable of elastic deformation at both room temperature and a temperature of said cryogenic cutting fluid.

14. The apparatus of claim 13, wherein said seal member comprises Teflon®.

15. The apparatus of claim 9, said inside surface of said housing member having a groove at a rotatable coupling portion thereof and said coupling region of said rotatable cutting assembly having a corresponding groove at a rotatable coupling portion thereof, and further comprising a plurality of ball bearings lying in a channel defined by said grooves to effect rotatable coupling of said rotatable cutting assembly and said rotary coupling.

16. The apparatus of claim 15, wherein said rotatable cutting assembly comprises a tool holder member and a sleeve member circumferentially encompassing said tool holder member, each of said at least one cryogenic cutting fluid inputs being holes in said sleeve member, and each of said at least one cryogenic cutting fluid delivery lines being fluidly coupled to a corresponding hole in said sleeve member, and wherein said said inner surface of said seal member includes at least one lip on opposite sides of said opening, wherein at least a first lip is sealably coupled to a portion of said sleeve member of said rotatable cutting assembly on a first side of said input and a second lip is sealably coupled to a portion of said sleeve member of said rotatable cutting assembly on an opposite side of said input.

17. The apparatus of claim 16, wherein said seal member comprises a material capable of elastic deformation at both room temperature and a temperature of said cryogenic cutting fluid.

18. The apparatus of claim 17, wherein cryogenic cutting fluid is liquid nitrogen.

19. The apparatus of claim 18, wherein said seal member comprises Teflon®.

20. A method for delivering a cryogenic cutting fluid from a fixed supply line to a cutting edge of a rotatable cutting assembly, comprising the steps of:

(a) supplying a cryogenic cutting fluid from said fixed supply line to at least one cryogenic cutting fluid input in a rotatable cutting assembly substantially without leaking therebetween;

(b) delivering said cryogenic cutting fluid supplied to said at least one input through at least one cryogenic cutting fluid delivery line; and

(c) applying substantially all of said delivered cryogenic cutting fluid to said cutting edge of said rotatable cutting assembly.

21. The method of claim 20, wherein said supplying step comprises:

(i) receiving a cryogenic cutting fluid from said fixed supply line;

(ii) passing said cryogenic cutting fluid through at least one channel in a housing member of a rotary coupling; and

(iii) advancing said cryogenic cutting fluid through at least one channel in an elastically deformable seal member of said rotary coupling to thereby supply said at least one cryogenic cutting fluid input with said cryogenic cutting fluid while substantially avoiding leaks.

22. The method of claim 21, wherein said advancing step comprises advancing said cryogenic cutting fluid through a channel in a Teflon® seal member of said rotary coupling.

23. The method of claim 20, wherein said delivering step comprises delivering said cryogenic cutting fluid through at least one channel bored into said rotatable cutting assembly.

24. The method of claim 20, wherein said delivering step comprises delivering said cryogenic cutting fluid through at least one tube mounted on said rotatable cutting assembly.

25. The method of claim 20, wherein said applying step comprises expelling said cryogenic cutting fluid from expelling ends of said at least one cryogenic cutting fluid delivery lines that are formed an angle β relative to the flow of said cryogenic cutting fluid to thereby induce a spreading of said cryogenic cutting fluid and distribute said cryogenic cutting fluid upon a wearing area of said cutting portion of said cutting tool.

26. The method of claim 20, wherein said applying step comprises passing said cryogenic cutting fluid delivered by said at least one cryogenic cutting fluid delivery lines through at least one nozzle to distribute said cryogenic cutting fluid upon a wearing area of said cutting portion of said cutting tool.

27. A rotary coupling for mechanically coupling at least one fixed cryogenic cutting fluid supply lines to a rotatable cutting assembly and permitting a cryogenic cutting fluid to flow from said supply line to said cutting assembly substantially without leaking therebetween, said rotatable cutting assembly being circular in shape in at least a coupling region and having at least one cryogenic cutting fluid input in said coupling region, comprising:

(a) a housing member having an outside surface thereof, a circular cutting assembly opening forming an inside surface thereof and being sufficiently large to encompass said coupling region of said rotatable cutting assembly, and at least one cryogenic cutting fluid channel traversing said housing member from a portion of said outside surface to a portion of said inside surface, wherein each of

said at least one cryogenic cutting fluid channels is fluidly coupled to one of said one or more supply lines at said outside surface to thereby permit said cryogenic cutting fluid to flow from said supply line to said inside surface; and

(b) a ring-shaped seal member having a first surface sealably coupable to a portion of said coupling region of said rotatable cutting assembly, a second surface coupled to a portion of said inside surface of said housing member, and an opening traversing said seal member from said inside surface to said outside surface and alignable with at least one of said cryogenic cutting fluid channels and with one of said inputs to thereby permit said cryogenic cutting fluid to flow from said inside surface of said housing member to said rotatable cutting assembly without substantial leakage therebetween.

28. The apparatus of claim 27, wherein said seal member comprises a material capable of elastic deformation at both room temperature and a temperature of said cryogenic cutting fluid.

29. The apparatus of claim 28, wherein said seal member comprises Teflon®.

30. The apparatus of claim 27, wherein said inner surface of said seal member includes at least one lip on opposite sides of said opening, wherein at least a first lip is sealably coupleable to a portion of said coupling region of said rotatable cutting assembly on a first side of said input and a second lip is sealably coupleable to a portion of said coupling region of said rotatable cutting assembly on an opposite side of said input.

31. The apparatus of claim 30, wherein said seal member comprises a material capable of elastic deformation at both room temperature and a temperature of said cryogenic cutting fluid.

32. The apparatus of claim 31, wherein said seal member comprises Teflon®.

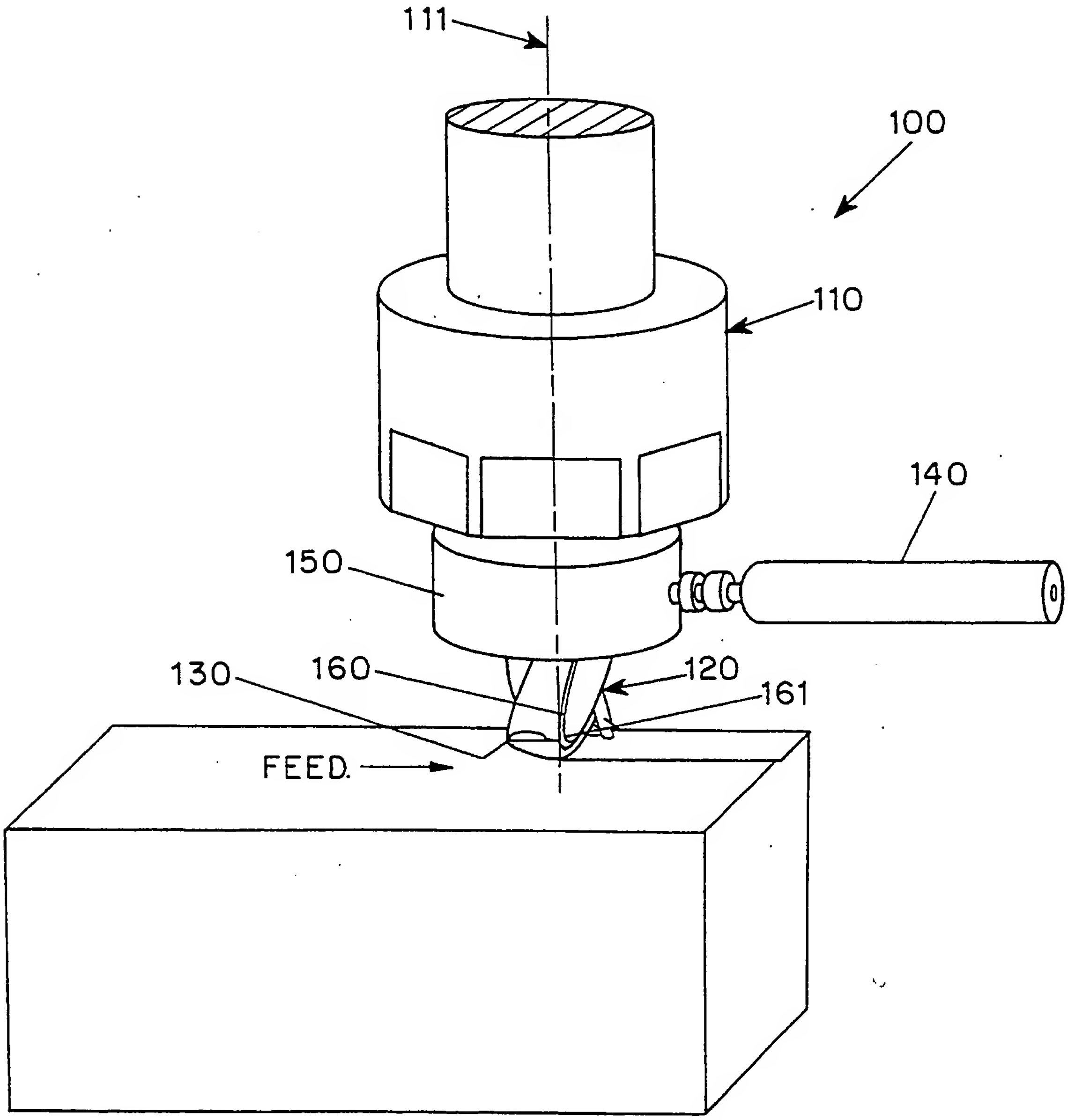

FIG. 1

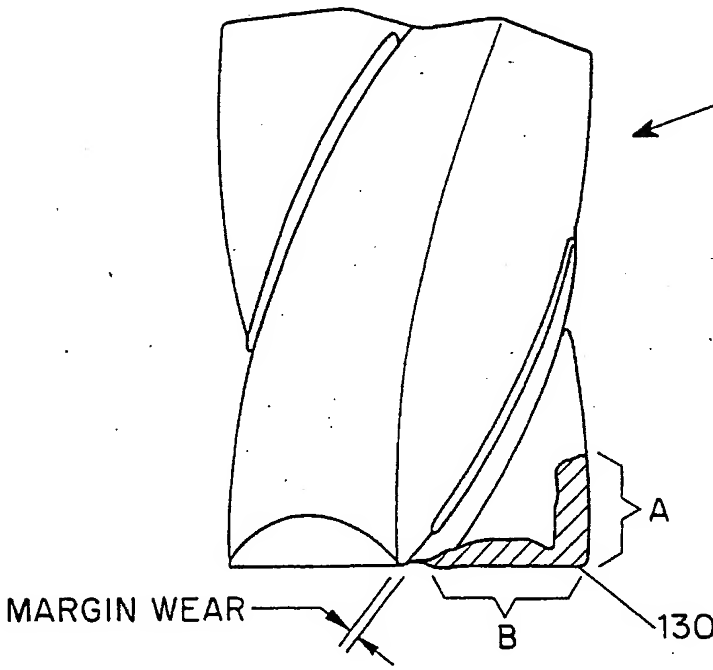

FIG. 2a

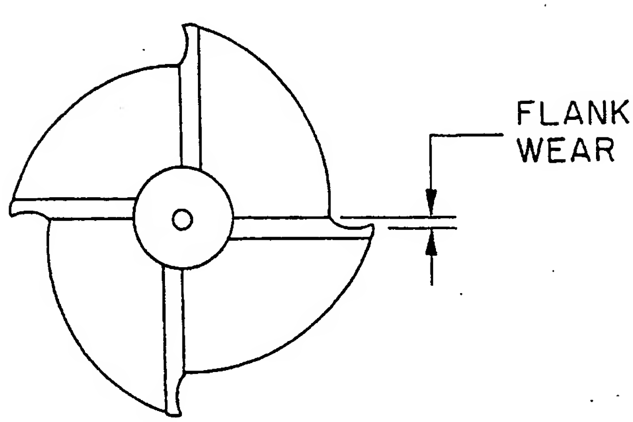

FIG. 2b

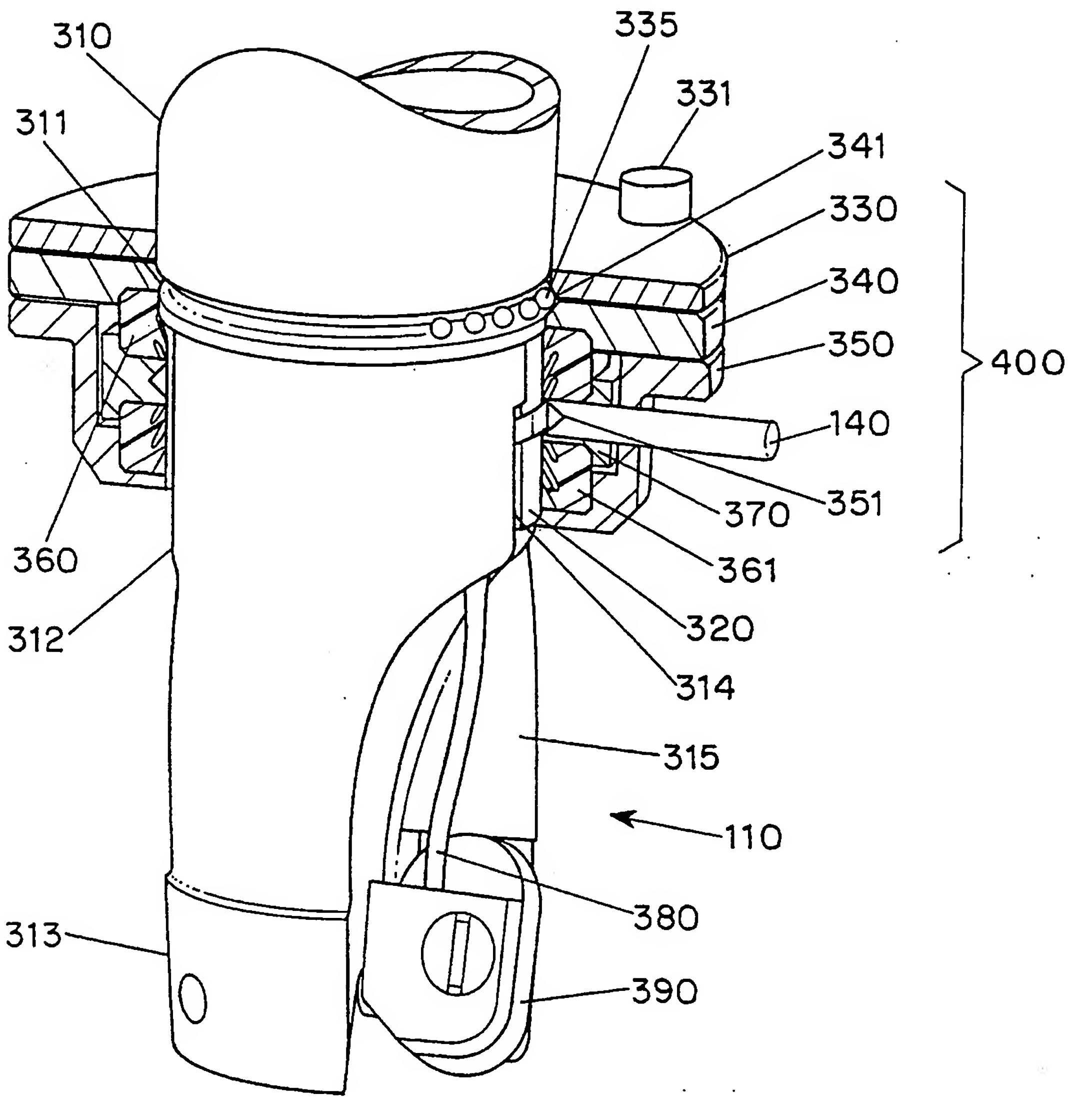
310
335
331
311
341
330
340
350
400
140
351
370
360
361
320
312
314
315
110
380
313
390

FIG. 3

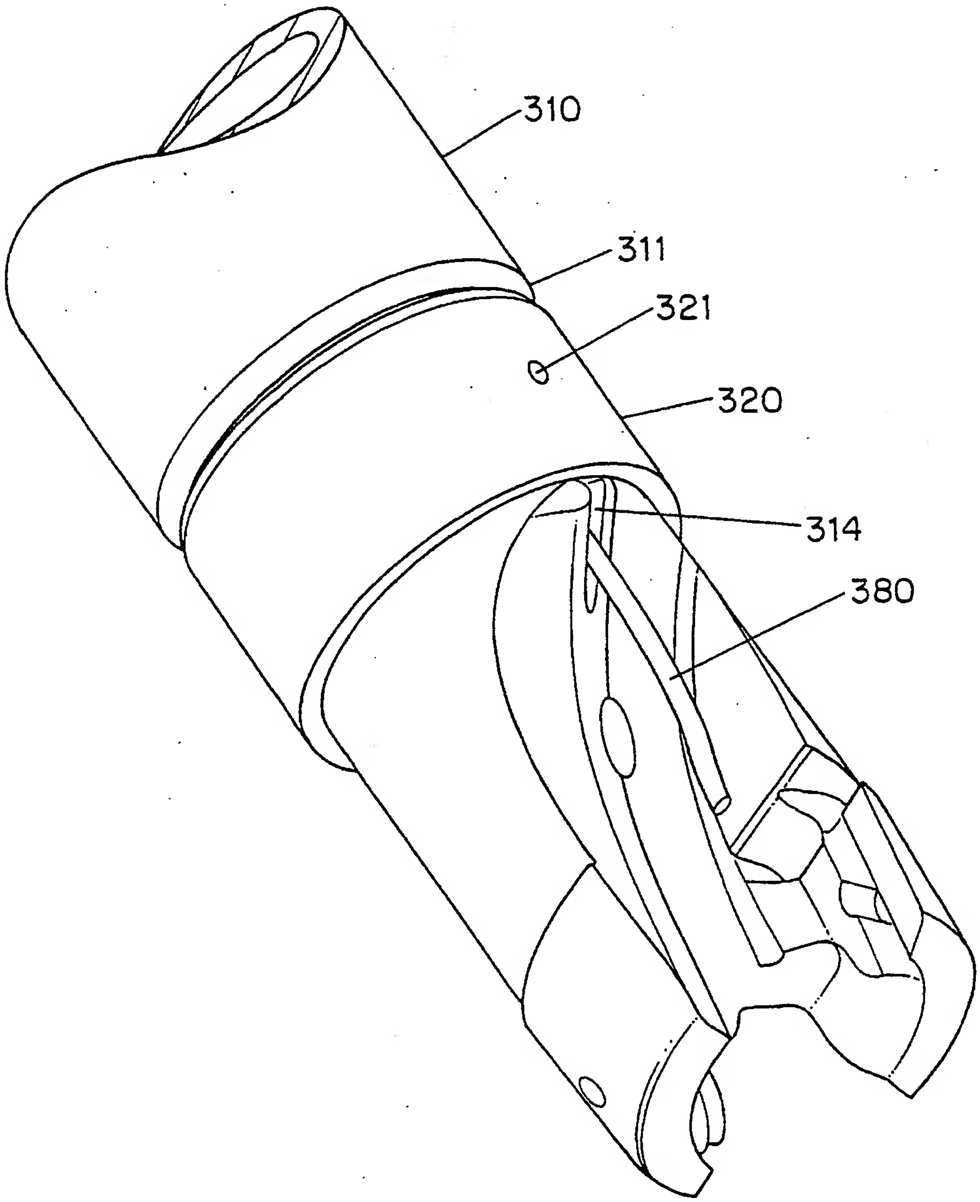

FIG. 4

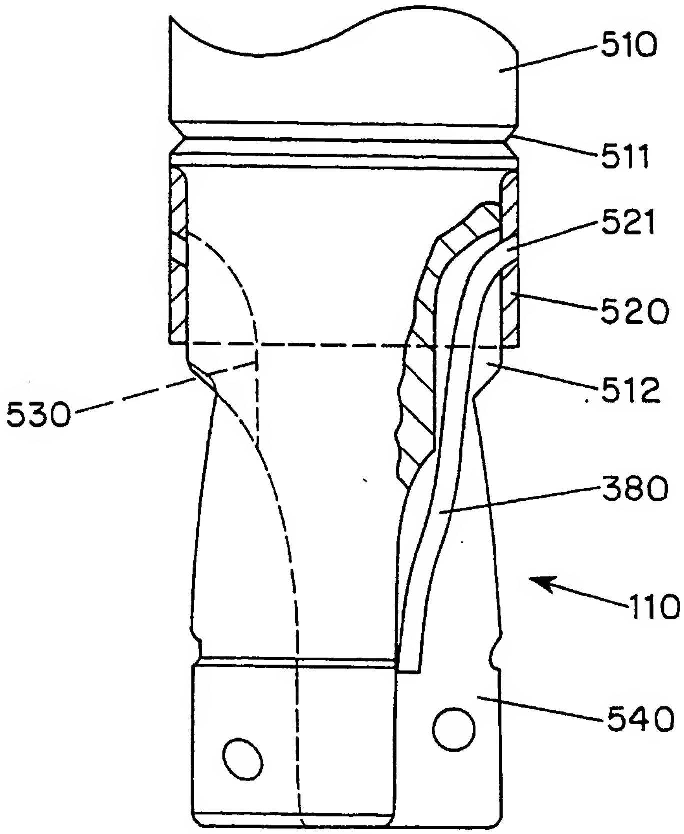

FIG. 5a

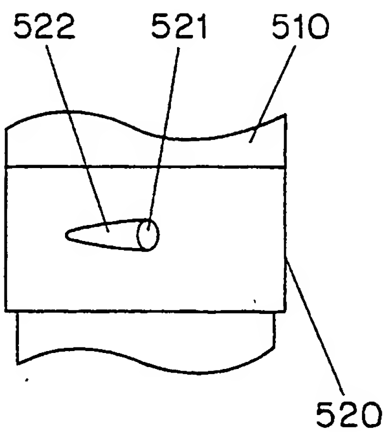

FIG. 5b

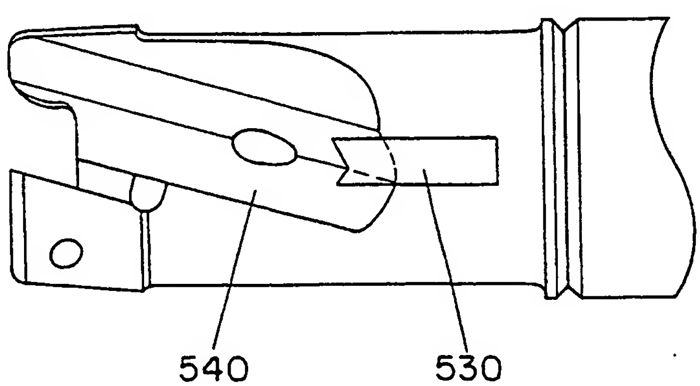

FIG. 5c

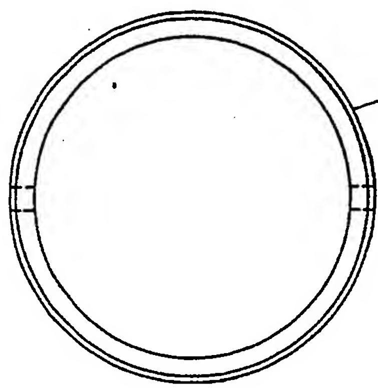

FIG. 6a

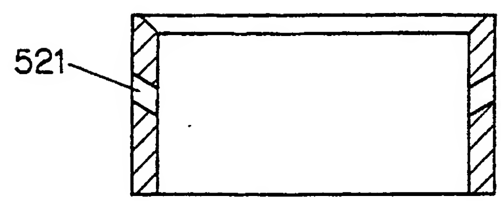

FIG. 6b

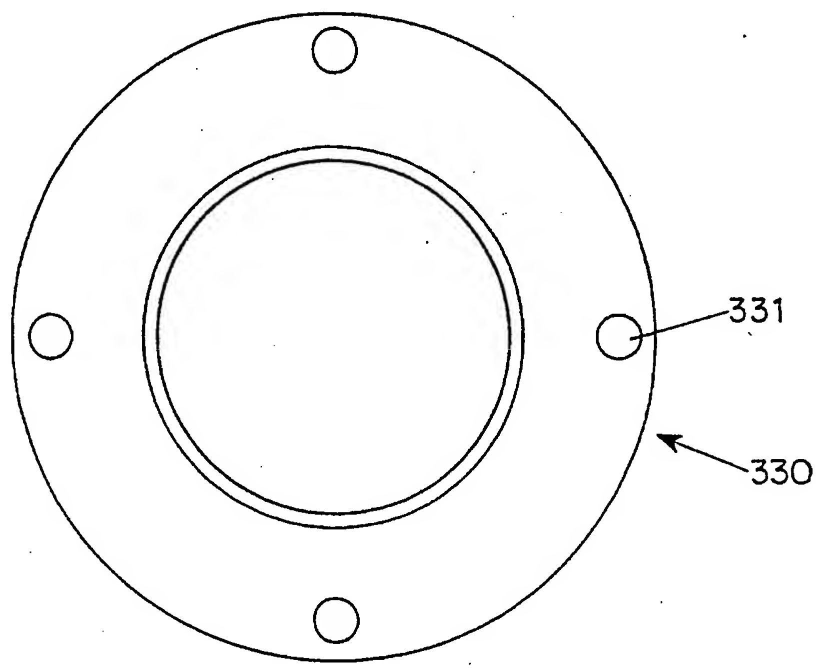

FIG. 7a

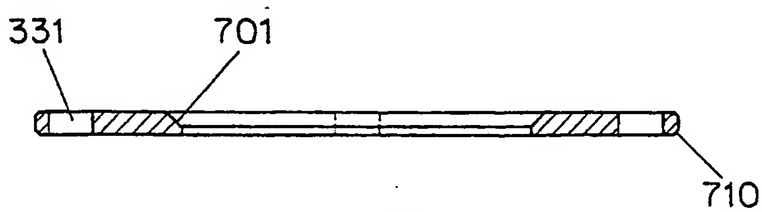

FIG. 7b

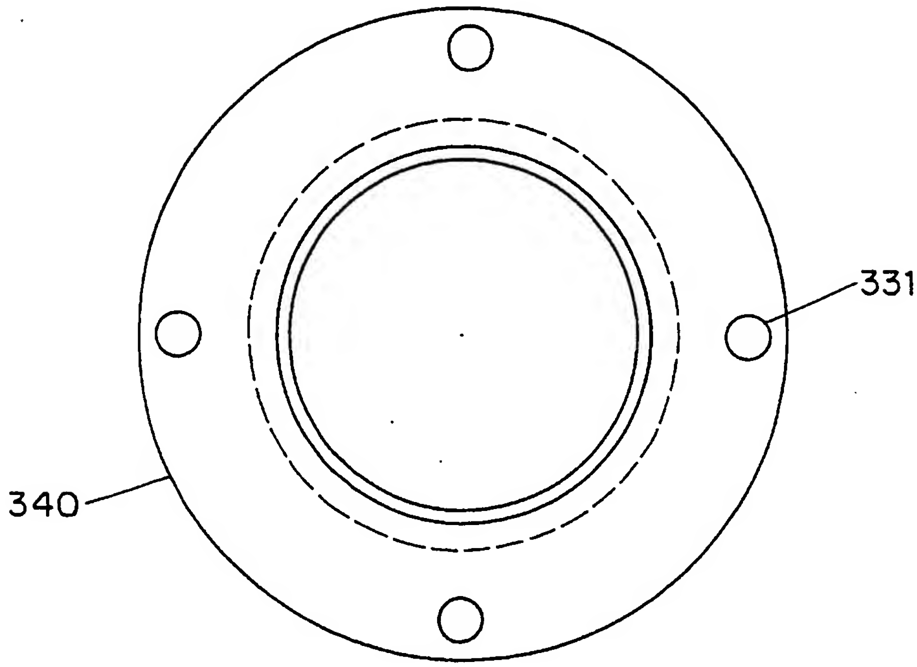

FIG. 8a

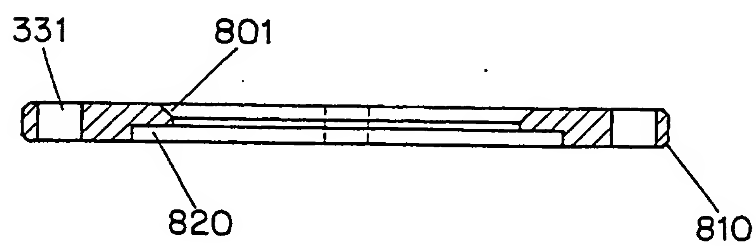

FIG. 8b

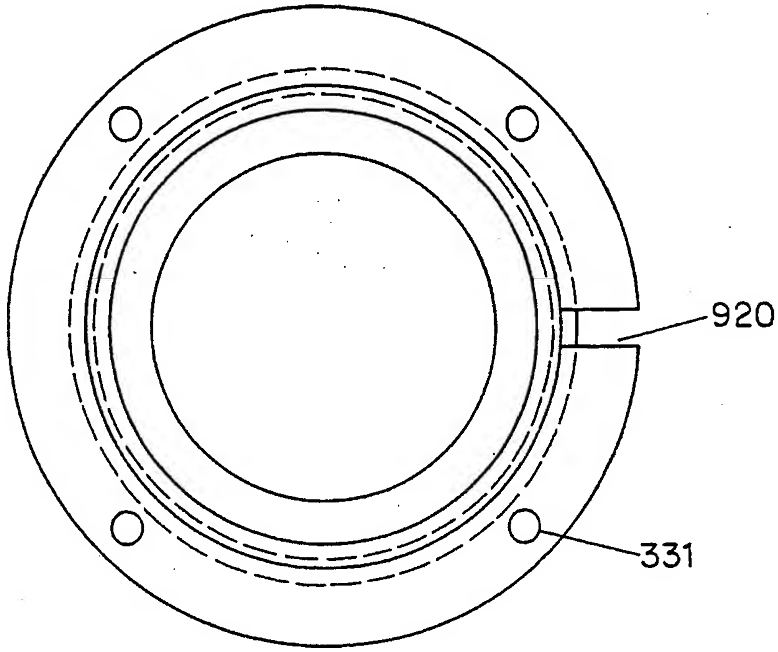

FIG. 9a

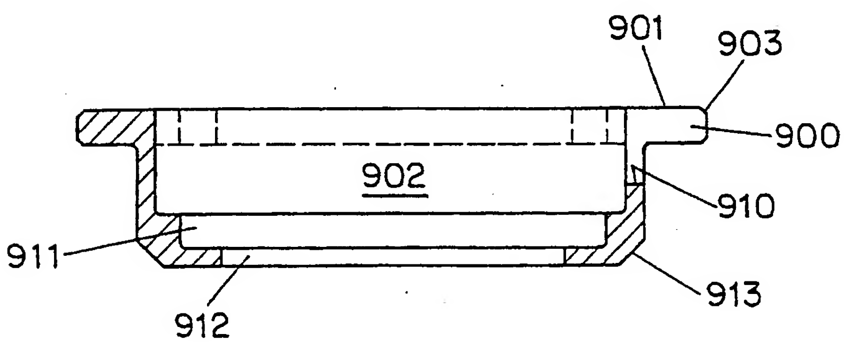

FIG. 9b

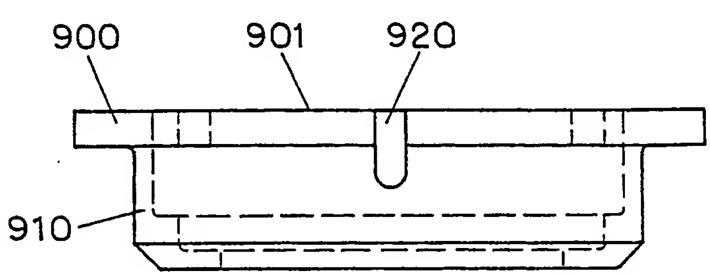

FIG. 9c

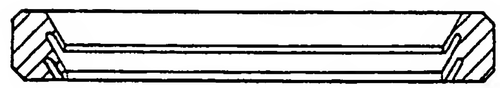

FIG. 10a

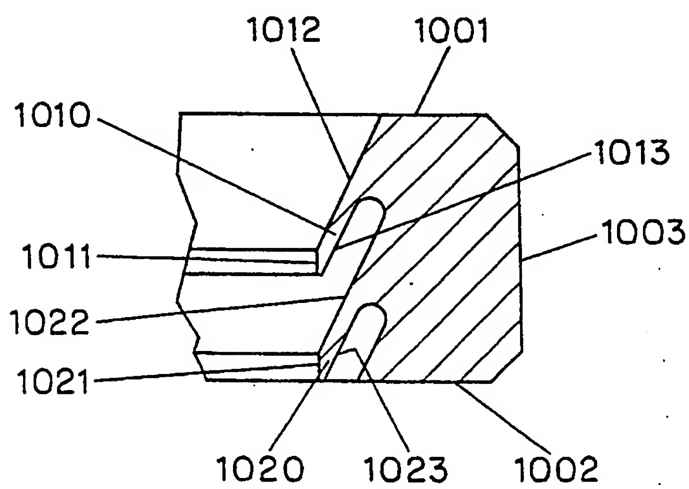

FIG. 10b

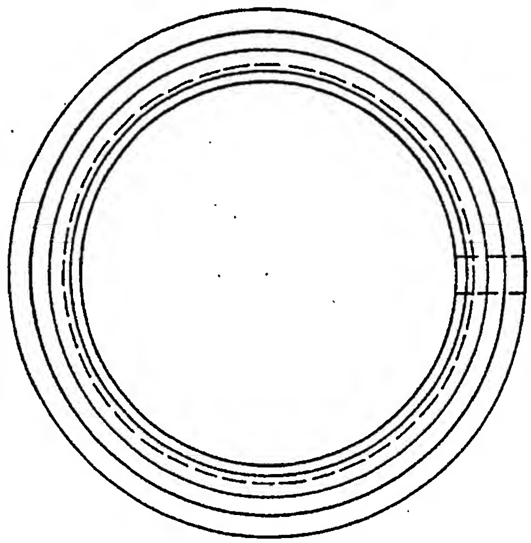

FIG. 11a

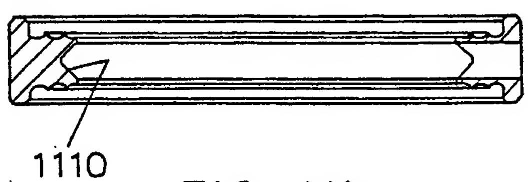

FIG. 11b

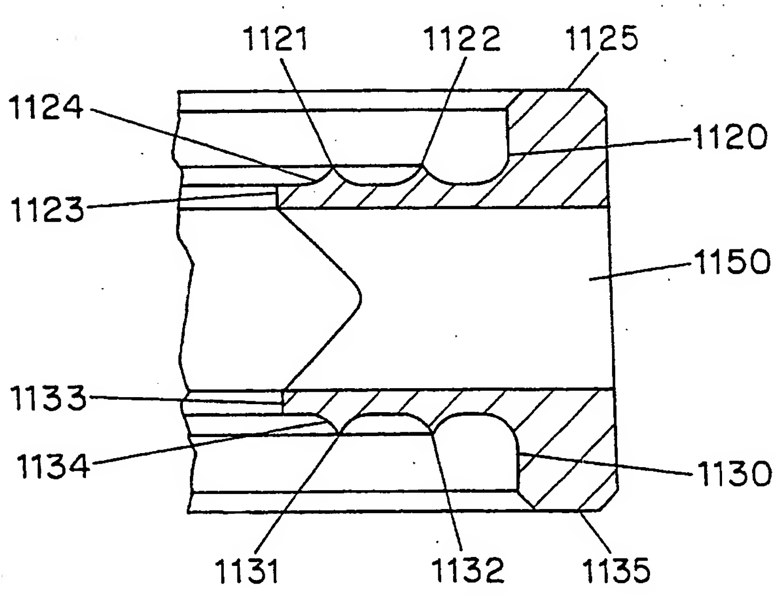

FIG. 11c

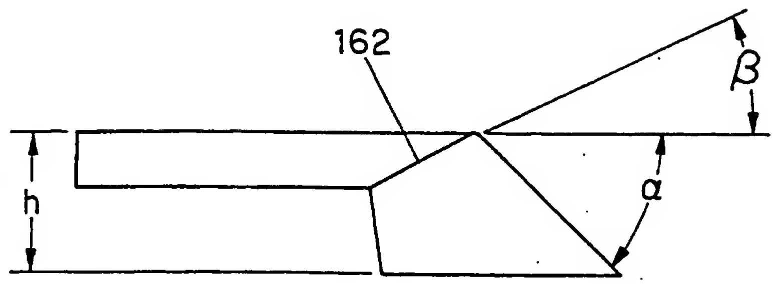

FIG. 12a

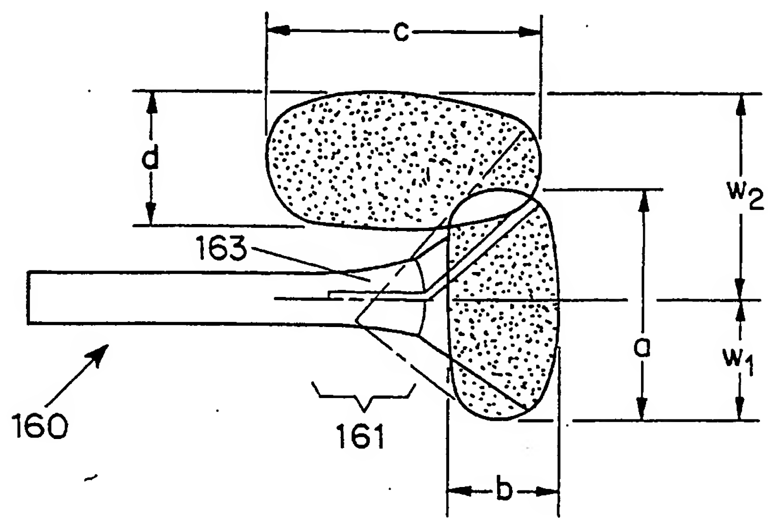

FIG. 12b

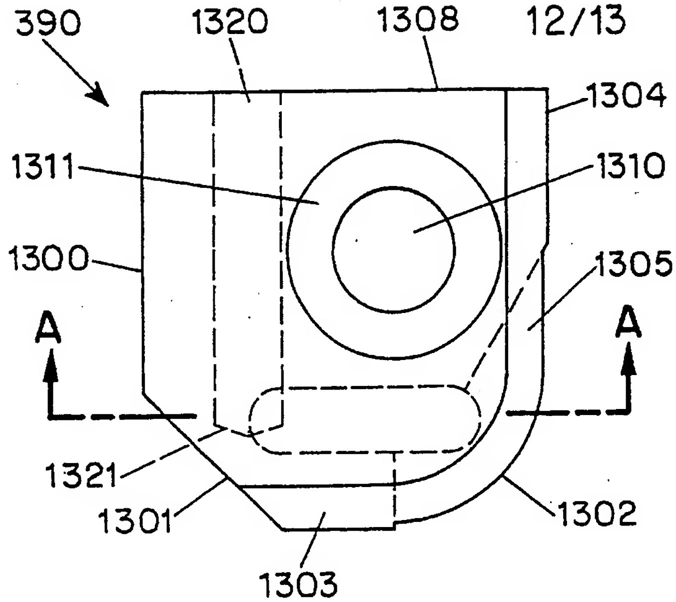

FIG. 13a

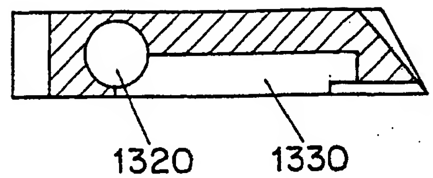

FIG. 13D

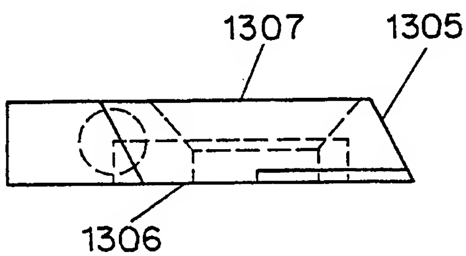

FIG. 13b

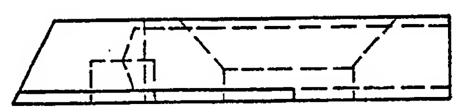

FIG. 13c

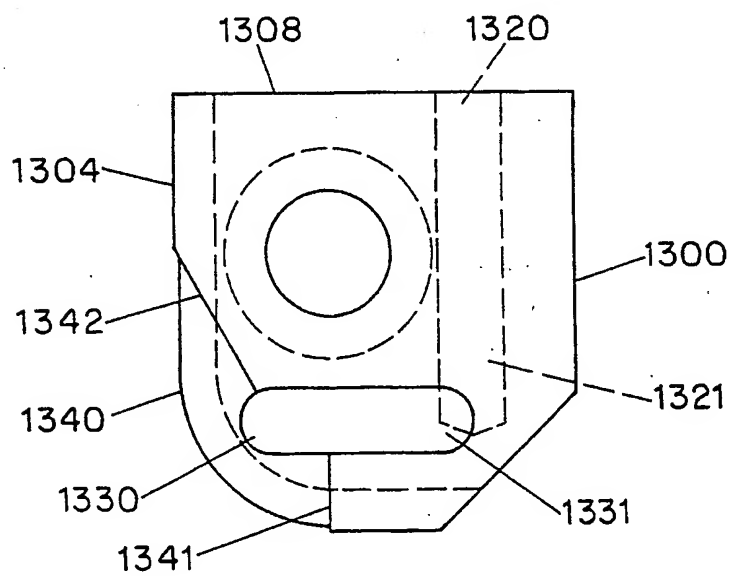

FIG. 13e

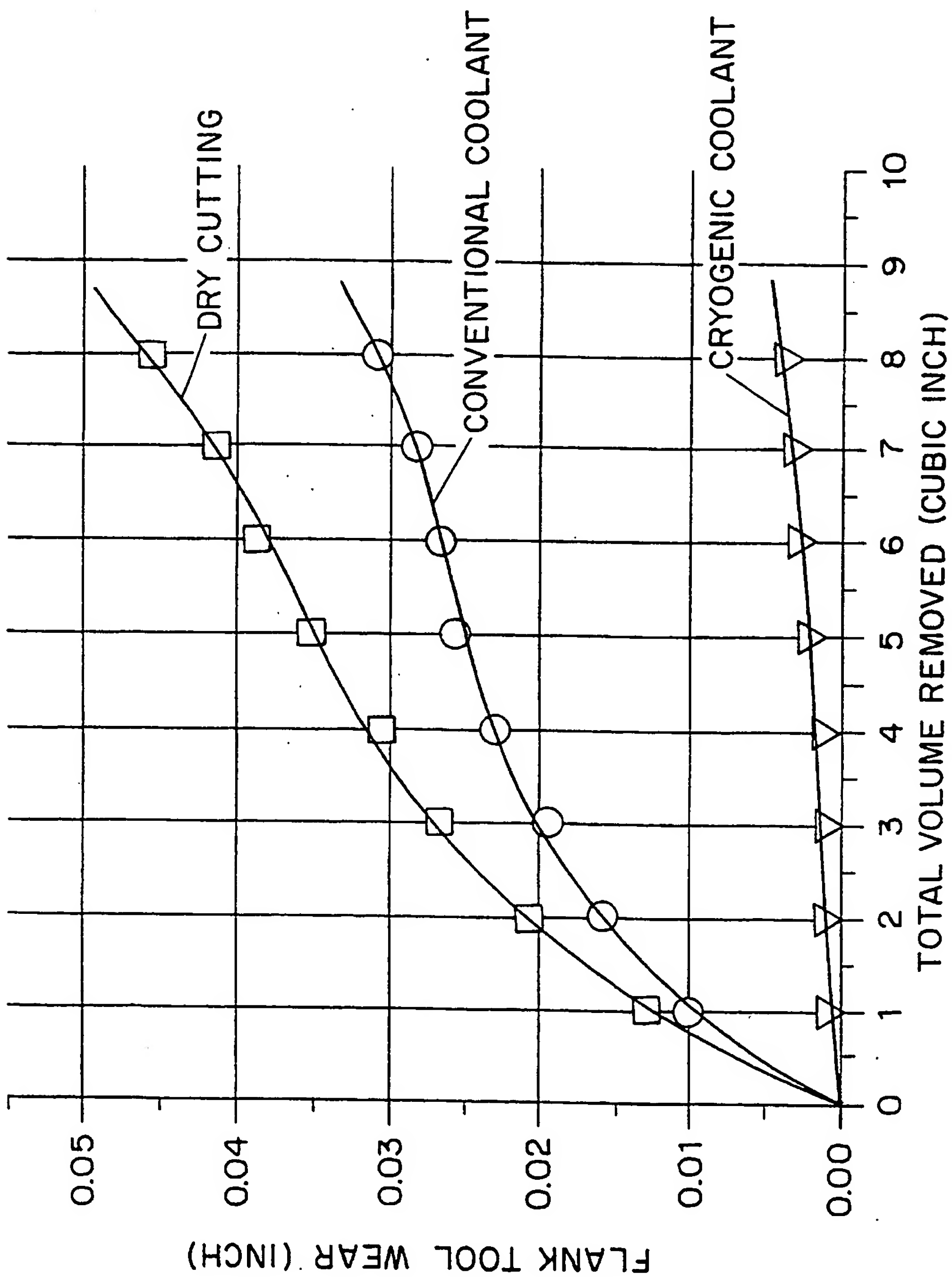
DRY CUTTING
CONVENTIONAL COOLANT
CRYOGENIC COOLANT
0.05
0.04
0.03
0.02
0.01
0.00
FLANK TOOL WEAR (INCH)
0
1
2
3
4
5
6
7
8
9
10
TOTAL VOLUME REMOVED (CUBIC INCH)

FIG. 14